QUANTUM PHASES AT THE NANOSCALE

NANOPHASE

Erice 15 July-20 July 2002

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Novel quantum phases at the nanoscale; Quantum Hall ferromagnetism; Luttinger liquids and Wigner crystal
Spin phases in low-dimensional semiconductor and superconductors; Excitonic insulators and metal-insulator transitions; Non-conventional materials and new directions; Ferromagnetic semiconductor materials and devices; Molecular crystal devices; Giant and colossal magnetoresistance materials; Biomolecular nanosystems; Carbon nanotubes; Metallic nanoparticles; New experimental and theoretical approaches at the nanoscale; Scanning-probe techniques; Quantum criticality and Nanofabrication

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QUANTUM PHASES AT THE NANOSCALE

NANOPHASE

Fundamental nanoscale science will foster the creation of novel technologies in electronics, optoelectronics, communications and information processing. Studies of the nanoscale will spun new research directions in contemporary and future condensed matter physics. Participants in **NANOPHASE** will present and discuss new fundamental quantum effects occurring at the nanoscale. We are certain the conference will stimulate the exchange of ideas, disseminate the most recent experimental and theoretical results, and promote training of young researchers entering the field. The topics debated in NANOPHASE cover intriguing and innovative aspects of novel quantum phases and quantum phase transitions in condensed matter systems of greatly reduced physical dimensions. The presentations highlight general concepts and explore new frontiers and directions of research. The program covers three broad areas:

Novel quantum phases at the nanoscale, such as those that emerge in fractional and integer quantum Hall systems, in low-dimensional superconductors and semiconductors, in Luttinger liquids, in excitonic instabilities, etc.

Non conventional materials and new directions, topics include nanomagnetism, new correlated phases in ferromagnetic semiconductors, molecular crystals, nanoparticles, manganites, biomolecular nanosystems and carbon nanotubes, etc.

New experimental and theoretical approaches at the nanoscale, that addresses issues in advanced scanning-probe techniques; new approaches to nanofabrication; new theoretical approaches to quantum criticality and quantum phase transitions at the nanoscale.

The conference is sponsored by the European Commission (EC), the National Science Foundation (NSF), the Office of Naval Research (ONR and ONRIFO), the European Office of Aerospace Research & Development (EOARD), the National Enterprise for nanoScience and nanoTechnologies (NEST-INFM) and the Ettore Majorana centre for scientific culture. The support of these agencies and research institutes is gratefully acknowledged.

We look forward to a productive and enjoyable Conference. Erice is a beautiful area that also offers great opportunities for extra-curricular activities in culture and tourism.

Fabio Beltram, Elisa Molinari, Aron Pinczuk, Vittorio Pellegrini and Carlos Tejedor

Erice 15 July – 20 July 2002

Carbon Nanotube as Phase-Coherent Quantum Cylinder

Tsuneya Ando
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A carbon nanotube is composed of concentric tubes of rolled two-dimensional graphite sheets, on which hexagons are arranged in a helical fashion about the axis. Since the first discovery quite a number of studies have been reported on their electronic properties because of their unique topological structures. There have been a lot of experimental works focusing on the transport measurement in various nanotube structures. Meanwhile, the conductance of carbon nanotubes has been calculated using different approaches. The purpose of this talk is to give a brief review on recent theoretical investigations on transport properties of carbon nanotubes. The topics include an effective-mass description of electronic states, absence of backward scattering except for scatterers with a potential range smaller than the lattice constant and some examples of related experiments, a conductance quantization in the presence of short-range and strong scatterers such as lattice vacancies, phonons and electron-phonon scattering, contacts with a metallic electrode, and junctions and topological defects. Some of the topics are described also in a review article [T. Ando, Semicond. Sci. Technol. **15**, R13 (2000)].

Time Domain Capacitance Spectroscopy of the Two-Dimensional Electron Gas

Raymond C. Ashoori
MIT Cambridge, MA 02139, (USA)

This talk describes results from a new technique capable of measuring the tunneling current into both localized and conducting states in a 2D electron system. We call this AC pulsing method "Time-Domain Capacitance Spectroscopy" (TDCS), and it produces *I-V* characteristics for tunneling with no distortions arising from low 2D in-plane conductivity. In a perpendicular magnetic field, a pseudogap develops in the tunneling density of states at the Fermi energy. We resolve a linear energy dependence of this pseudogap at low excitations and find that it has a linear form over a wide range of magnetic fields. While no theory for this linear form exists, we believe that the data are suggestive of a simple Coulomb charging picture. Further, in explorations of the effect of quantum Hall states on tunneling, we have found that for most noninteger filling factors, tunneling can be characterized by a single, well-defined tunneling rate. However, for spin-polarized quantum Hall states (n _ 1, 3, and 1_3) tunneling occurs at two distinct rates that differ by up to 2 orders of magnitude. The dependence of the two rates on temperature and tunnel barrier thickness suggests that slow in-plane spin relaxation creates a bottleneck for tunneling of electrons.

In collaboration with H.B. Chan, A. Siddiqui, L.N. Pfeiffer, and K.W. West

Spin gating and nuclear imprinting in semiconductor nanostructures

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There is a growing interest in the use of electronic and nuclear spin in semiconductor nanostructures as a medium for the manipulation and storage of classical and quantum information. Femtosecond-resolved optical experiments reveal a remarkable resilience of electronic spin states to environmental decoherence in a variety of bulk semiconductors, heterostructures, and quantum dots. Spin lifetimes are seen to exceed hundreds of nanoseconds, enabling the transport of coherent spin packets over hundreds of microns. Furthermore, coherent spin information can flow across interfaces of dissimilar materials in engineered structures over a broad range of temperatures, and the transport of spin information can be controlled with both electric and magnetic

fields [1]. Recent experiments show that the electron g-factor can be continuously tuned by displacing the wave function within spin-engineered nanostructures [2]. Gate-voltage mediated control of coherent spin precession is demonstrated, including complete suppression of precession, reversal of the sign of *g*, and operation up to room temperature. In addition, hybrid ferromagnet/semiconductor systems have the potential for controlling coherent states by combining photonic, electronic, and magnetic manipulation of spin, thereby introducing new possibilities for engineering multifunctional spin-based electronics. Dynamical measurements in a series of hybrid structures unexpectedly reveal that the magnetization of a ferromagnet can be "imprinted" into the nuclear spin system [3]. Surprisingly, photoexcited electrons in the semiconductor are observed to spontaneously spin-polarize due to the proximity of an epitaxial ferromagnetic metal [4], exhibiting coherent dynamics that persist over time scales comparable in magnitude to traditional optical injection. [1] I. Malajovich *et al.*, *Nature* **411**, 770 (2001). [2] G. Salis *et al.*, *Nature* **414**, 619 (2001). [3] R.K. Kawakami *et al.*, *Science* **294**, 131 (2001). [4] R.J. Epstein *et al.*, *Phys. Rev. B Rapid Commun.* **56**, 121202 (R), (2002).

Engineered Green Fluorescent proteins for proteomics and biomolecular electronics

Fabio Beltram
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The reversible photoinduced structural changes of a green fluorescent protein (GFP) mutant and their optical control will be presented. A photoreversible optically-inactive configuration will be demonstrated with absorption peak at 365 nm which is consistent with a photoisomerization pathway associated to hydrogen-bond breaking in the chromophore environment. We show that this state is involved in the peculiar switching dynamics of these molecules and we determine the transition rates of the reversible photoconversion processes. These experiments combine to provide the framework for the implementation and optimization of efficient room temperature GFP-based all-optical memories that use the fluorescent properties of these proteins. Applications to HIV-1 proteomics will also be presented.
Work done in collaboration with: Riccardo Nifosì, Aldo Ferrari, Caterina Arcangeli, Vittorio Pellegrini, Mauro Giacca, Valentina Tozzini

Spins, charges and currents at Domain Walls in a Quantum Hall Ising Ferromagnet.

Luis Brey
Instituto de Ciencia de Materiales de Madrid-CSIC, Spain

We study spin textures in a quantum Hall Ising ferromagnet. Domain walls between ferro and unpolarized states at $\nu=2$ are analyzed with a functional theory supported by a microscopic calculation. In a neutral wall, Hartree repulsion prevents the appearance of a fan phase provoked by a negative stiffness. For a charged system, electrons become trapped as solitons at the domain wall. The size and energy of the solitons are determined by both Hartree and spin-orbit interactions. Finally, we discuss how electrical transport takes place through the domain wall. Work in collaboration with Carlos Tejedor.

Quantum transport in nanotube-based structures

Marco Buongiorno Nardelli
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Although the field of carbon nanotubes has seen an explosive growth due to the

substantial promise of these molecular structures in novel nanoscale electronic devices, fundamental questions about their electrical transport properties remain to be answered. In particular, the processing and positioning of individual nanotubes as specific device components is likely to introduce large mechanical deformations in nanotube geometry, which will modify the electronic and transport behavior of the system. Using state of the art quantum calculations, we have studied the electronic and transport properties of a variety of nanotube-based structures relevant for the design of nanoscale electronic devices. In particular, we have examined the influence of mechanical deformations and/or disordering in carbon nanotubes and discovered several classes of behavior. Our results show that bent armchair tubes keep their metallic character for most practical purposes, while metallic chiral nanotubes undergo a bending-induced metal semiconductor transition that manifests itself in the occurrence of effective barriers for transmission. We have demonstrated the possibility of forming intra-tube junctions and conducting electrical contacts via the rebonding of open-ended NT's that are put in close proximity to each other. We will examine the behavior of nanotube-metal contacts and explain the anomalously large contact resistance observed in nanotube devices as due to the spatial separation of their conductance eigenchannels. The results for various contact geometries and strategies for improving device performance will be discussed. Finally, we have theoretically demonstrated that carbon nanotube-metal cluster assemblies behave as effective chemical sensors. Using an Al cluster attached to a metallic nanotube we have created an effective semiconducting nanowire whose electrical response is found to dramatically change upon NH$_3$ adsorption to the metal cluster. We will discuss the relation between the electronic response and the mechanism of molecular sensing and present possible ways to improve upon different species detection.

Observation of sharp collective excitations of the one-dimensional electron gas in cleaved-edge-overgrown semiconductor quantum wires

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Coulomb interactions in a dilute one-dimensional electron system in high quality cleaved edge overgrown GaAs quantum wires are probed by optics experiments. The wires display one-dimensinal photoluminescence emissions, indicating the presence of one-dimensional subbands occupied by a dilute 1D-electron gas. Both inter-subband and intra-subband collective excitation modes are observed in resonant inelastic light scattering spectra. A sharp intra-subband excitation occurs close to the single particle transition energy. It is narrower and much weaker than the plasmon band, and its width is consistent with electron mean free paths in the micrometer range. Scattering intensities display large enhancements only for scattered photon energies in resonance with the optical gap of the wires. Interpretation in terms Luttinger liquid bosons needs to consider this resonance in the outgoing channel. Preliminary analysis reveals impact of interactions in the 1D system.

Spin Electronics and Spin Computation

Sankar Das Sarma
Condensed Matter Theory Center, University of Maryland, USA

I will discuss, time permitting, various theoretical aspects of the following topics in spintronics: (1) fundamental mechanisms

underlying ferromagnetism in diluted magnetic semiconductors; (2) physics of spin-polarized transport in semiconductor nanostructures; (3) quantum computation using electron spin qubits in semiconductor nanostructures; (4) spin relaxation in semiconductor nanostructures. The work has been done in collaboration with Euyheon Hwang, Alexei Kaminski, Amit Chattopadhyay, Igor Zutic, Jaroslav Fabian, Xuedong Hu, Belita Koiller, and Rogerio de Sousa, and has been supported by US-ONR, DARPA, ARDA, LPS, and NSF.

Electromagnetic response of isolated Aharonov-Bohm rings

R. Deblock[1,2*], Y. Noat[2], B.Reulet[2], D.Mailly[3] and H. Bouchiat[2]

[1]*Department of Applied Physics, Delft University of Technology. The Netherlands.*
[2]*Laboratoire de Physique des Solides, Université Paris-Sud, Orsay, France.*
[3]*Laboratoire de Photonique et Nanostructures, Marcoussis, France.*

In connected mesoscopic samples because of the strong coupling to the environment effects due to electronic interferences are small compared to the Drude conductance. On the contrary the conductance measured on an isolated sample submitted to an electromotive force is dominated by quantum effects. In this spirit we have measured the electromagnetic response of isolated rings coupled to a superconducting micro resonator. The orbital magnetism of silver rings and rings etched in the two-dimensional electron gas of a GaAlAs/GaAs heterojunction reveals the existence of an imaginary part of the conductance associated with a non-dissipative current circulating in the rings, the persistent current. The low-field diamagnetism measured in those systems is difficult to explain by theoretical predictions on persistent current. We also measured an important flux dependent contribution to the electric dipolar response at finite frequency of the GaAs rings due to the effect of electronic interferences on electric screening. This new mesoscopic effect is one order of magnitude bigger than the magnetic response.

References: R. Deblock, Y. Noat, H. Bouchiat, B. Reulet and D. Mailly, Phys. Rev. B **65**, 075301 (2002). R. Deblock, Y. Noat, H. Bouchiat, B. Reulet and D. Mailly, Phys. Rev. Lett. **84** (23), 5379 (2000). R. Deblock, R. Bel, B. Reulet, H. Bouchiat and D. Mailly, cond-mat/0109527.

Spin polarized injection from manganite into conjugated oligomer at room temperature

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Direct spin polarized(SP) injection was observed on hybrid planar devices $La_{0.7}Sr_{0.3}MnO_3$ - sexithiophene - $La_{0.7}Sr_{0.3}MnO_3$ at room temperature. High quality epitaxial $La_{0.7}Sr_{0.3}MnO_3$ films (Curie temperature $T_C \approx 350$ K) were deposited by Channel-Spark ablation technique. Electron bean lithography was used to create planar two-electrode devices with electrodes separated by 100-500 nm. Subsequently, sexithiophene (T_6) thin films were deposited by ultra high vacuum molecular beam deposition in order to bridge electrically the two electrodes. $La_{1-x}Sr_xMnO_3$ (0.2>x>0.5), known as a colossal magnetoresistance (CMR) material, is a 100% SP ferromagnet at $T \ll T_c$: the metallic-like spin up band and the empty spin down band are separated by an approximately 1 eV energy gap due to a strong Hund rule coupling on manganese sites. This compound is an excellent spin polarized injector. T_6 is a conjugated rigid-rod organic semiconductor widely used in organic based electronics and showing a FET mobility up to 10^{-2} V^2 cm^{-1} s^{-1}. The films resistivity is about 10^6 Ohm cm at ambient conditions and is mainly governed by trap effects. A so called spin-valve experiment was performed at room temperature on the described planar devices. At zero magnetic field the electrodes spin polarizations are oriented randomly while in the magnetic field they orient parallel. Inserting the magnetic field (3.4 kOe) a strong decrease of the device

resistance was observed: the negative magnetoresistance (MR) is nearly 30% for T_6 bridges of the order of 100 nm. The MR decreases to 10% for 200 nm bridge lengths and disappears (MR=0) for lengths above 300 nm. Such a negative MR cannot be caused by T_6 itself (no MR was observed using non SP electrodes) and reflects the MR between two CMR electrodes, indicating that the spin polarization is not lost inside the organic semiconductor. The SP penetration length is roughly 200 nm at room temperature. These results promote the conjugated organic semiconductors as valuable materials for Spintronics applications.

Multi-terminal transport in 1D wires

Rafi De Picciotto
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Using a novel fabrication technique called cleaved edge overgrowth we have fabricated clean ballistic one-dimensional wires. Our fabrication scheme allows for additional probes to be attached along the wire. Further, the level of the invasiveness of these probes can be controlled. We present results on the temperature dependence of the conductance of such systems and elucidate the linear as well as non-linear response in such multi-terminal one-dimensional ballistic junctions.

Evidence of Landau levels and interactions of composite fermions

Irene Dujovne*
Department of Applied Physics and Applied Math, Columbia University, and Bell Labs, Lucent Technologies

I report inelastic light scattering experiments designed to identify the structure of spin-split levels of composite fermions (CF) and to determine strengths and impact of CF interactions.

Landau levels of composite fermions are explored in studies of low-lying spin excitations in the fractional quantum Hall states in the filling factor range $2/5 \geq$ [illegible] $> 1/3$. We observe low-lying spin-wave and magnetoroton excitations, in which the changes occur either in the spin or the charge degree of freedom, and new spin excitations that arise from spin-flip (SF) transitions with simultaneous change in the CF Landau level index. Observations of SF modes are key elements in the identification of the CF level structure from light scattering spectra. Near filling factors1/3 and 2/5 the observed low-lying modes offer evidence of well defined structure of Landau levels of composite fermions. Under a simple interpretation, the low-lying SF mode for $\nu \cong 1/3$, is used to determine the spin flip energy. This determination reveals significant interactions between quasiparticles. These 'residual' interactions could effectively drive the 2D system to condense into novel liquid states when there is partial population of a CF level. For filling factors in the range $2/5 > \nu > 1/3$ CF interactions should play roles in liquid states such as $\nu = 4/11$, 3/8 and 5/13.

In collaboration with Aron Pinczuk, Cyrus Hirjibehedin, Moonsoo Kang, Brian S. Dennis, Loren Pfeiffer and Ken West

*This work is supported in part by the Nanoscale Science and Engineering Initiative of the National Science Foundation under NSF Award Number CHE-0117752 and by the Keck Foundation

Evidence for Superfluidity in Double Layer 2D Electron Systems

J.P. Eisenstein
Caltech (USA)

Recent tunneling and Coulomb drag experiments on double layer 2D electron systems have offered remarkable new perspectives on the unusual bilayer quantized Hall state at total filling factor $\nu_{tot}=1$. This state, which may be described in a number of equivalent ways, including as an excitonic condensate or a quantum Hall ferromagnet, is predicted to exhibit a new kind of superfluidity. Distinct from the usual notion of zero resistance in ordinary quantum Hall systems, this new superfluidity involves counterflowing electrical currents in the two layers. In this talk I will summarize the experimental data which supports the

existence of this new form of dissipationless transport.

Scaling of Entanglement close to a Quantum Phase Transitions

Rosario Fazio
Scuola Normale Superiore, Pisa (Italy)

We discuss the entanglement near a quantum phase transition by analyzing the properties of the concurrence for a class of exactly solvable models in one dimension. We find that entanglement can be classified in the framework of scaling theory. Further, we reveal a profound difference between classical correlations and the non-local quantum correlation, entanglement: the correlation length diverges at the phase transition, whereas entanglement in general remains short ranged.

Kondo Effect and STM Spectra through Ferromagnetic Nanoclusters

Gregory A. Fiete, Gergely Zarand, Bertrand I. Halperin
Department of Physics, Harvard University (USA)
Yuval Oreg
Weizmann Institute of Science, Israel

Motivated by recent scanning tunneling microscope (STM) experiments on cobalt clusters adsorbed on single-wall metallic nanotubes [Odom et al. Science 290, 1549 (2000)], we study theoretically the size dependence of STM spectra and spin-flip scattering of electrons from finite size ferromagnetic clusters adsorbed on metallic surfaces. We study two models of nanometer size ferromagnets. (i) An itinerant model with delocalized s,p and d electrons and (ii) a local moment model with both localized d-level spins and delocalized cluster electrons. The effective exchange coupling between the spin of the cluster and the conduction electrons of the metallic substrate depends on the specfic details of the single-particle density of states on the cluster. The calculated Kondo coupling is inversely proportional to the total spin of the ferromagnetic cluster in both models and thus the Kondo temperature is rapidly suppressed as the size of the cluster increases. Mesoscopic fluctuations in the charging energies and magnetization of nanoclusters can lead to large fluctuations in the Kondo temperatures and a very asymmetric voltage dependence of the STM spectra. We compare our results to the experiments.

Quantum Size Effects in Molecular Magnets

Dante Gatteschi
Department of Chemistry, University of Florence, INSTM, Italy

The discovery that some molecules show slow relaxation of the magnetisation at low temperatures opened new exciting perspectives for the investigation of real systems where quantum and classical behaviour can be observed. Three classes of materials have been discovered so far, namely large molecules with large magnetic moment in the ground state showing slow relaxation of the magnetisation (Single Molecule Magnets, SMM); large antiferromagnetic molecules; one-dimensional ferro- or ferri-magnets showing slow relaxation of the magnetisation at low temperature. The first two classes can be considered as molecular magnetic quantum dots, the third as molecular magnetic quantum wires. In this communication a short review of the main systems investigated so far will be provided, with indications of open problems and perspectives.

Theory of scanning tunneling microscopy of metallic surfaces: Many-body effects and Friedel oscillations

Gabriele F. Giuliani
Purdue University (USA)

Motivated by the ability of accurately measuring via low temperature STM the local properties of metallic surfaces we have studied the problem of Friedel oscillations in two dimensional electronic systems. Both analytic as well as numerical results have been obtained for the exact - within linear response - oscillations of the electronic density and the energy resolved density of

states in the immediate proximity of an impurity. We have established that interaction effects beyond the simple random phase approximation must be properly accounted for a satisfactory description of the phenomenon.

Magneto-Rotons in Higher Landau Levels

Mark Oliver Goerbig and Cristiane Morais Smith
Département de Physique, Université de Fribourg, Pérolles, CH-1700 Fribourg

The dispersion of phonon-like collective excitations of 2D electrons confined to the lowest Landau level (N=0) exhibits a magneto-roton instability at finite wavevector, as shown by Girvin et al. in 1986. The interpretation of this instability is the following: the liquid phase, which displays the fractional quantum Hall effect, has a tendency towards Wigner crystallisation at low filling factors. On the other hand, Hartree-Fock calculations carried out by Fogler et al. in 1996 predict that the ground state in higher Landau levels is a charge density wave state. In order to obtain a common description for both phenomena, we generalise the theory of phonon-like excitations to higher Landau levels. Although the Laughlin liquid is a poor starting point for N>1, we expect that it nevertheless reveals the leading instability. We find an attenuation of the gaps and a shift of the magneto-roton position to smaller wavevectors with increasing Landau level index N.

Current and Shot Noise in Superconducting Junctions with a Quantum Dot in the Kondo Regime

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Transport through an Anderson impurity in the Kondo regime situated between two superconductors is considered. Here the analysis is performed within the slave boson mean field approximation. The new physics follows due to multiple Andreev reflections at the boundary between the dot and superconductor .The important new parameter that enters the transport characteristics is the ratio of the Kondo temperature to the superconducting gap. The current, shot noise power are displayed versus the applied bias voltage in the subgap region and found to be strongly dependent on this ratio. In particular, the I-V curve exposes an excess current in the limit of high Kondo temperature.

Spin injection in semiconductors: Linear and non-linear effects.

C. Gould, G. Schmidt, G. Richter, P. Grabs, A. Slobodskyy, and L.W. Molenkamp.
Physikalisches Institut (EP3), Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

Now that electrical injection and detection of spin polarized currents from dilute magnetic semiconductors into normal semiconductors has been established [1], it is essential that the details of controlling the effect be understood in order to be able to harness it's full potential. With this in mind, we study how the spin injection efficiency of our devices depends on external parameters such as magnetic field, injector thickness, and bias voltage. We compare the experimental results with relatively simple models of the transport, which fit the data well, and allow an intuitive understanding of the role of each of these parameters in spin injection. In particular, we find that to correctly explain the experimental observations, it is important to consider the effect of spin relaxation in the injector. This is required not only to understand the role of the injector thickness, but also to explain the shape of the magnetoresistance. We also find that the spin injection efficiency in the non-linear regime strongly depends on the applied voltage, which may impose important operational voltage limits on eventual spintronic devices. [1] G. Schmidt, G. Richter, P. Grabs, D. Ferrand, and L.W. Molenkamp, Phys. Rev. Lett. **87**, 22703 (2001).

T- and L- junction quantum wells: New device structures for investigating quantum Hall edges

M. Grayson[1], M. Huber[1], R. Deutschmann[1], M. Rother[1], D. Schuh[1], W. Wegscheider[1,2], W. Biberacher[3], M. Bichler[1], G. Abstreiter[1]
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Using special molecular beam epitaxy growth techniques, we introduce two new device geometries for studying quantum Hall effect (QHE) edge states. Both structures consist of two orthogonal quantum wells imbedded inside a GaAs/AlGaAs heterostructure, in either a T- or L-shaped junction. *T-junction quantum well (T-QW):* The T-QW under investigation was grown with a tunnel barrier at the T-junction, with translational invariance along this barrier guaranteeing lateral momentum conservation during tunneling. Applying a magnetic field B perpendicular to the stem of the T, we can perform momentum resolved tunnel spectroscopy of integer QHE edges. We observe peaks in the differential tunnel conductance that correspond to the enhanced density of states at the Landau levels, and by applying voltage bias and sweeping magnetic field, we can map the dependence of these features on energy and momentum, respectively. *L-junction quantum well (L-QW):* In a tilted B, the two 2-dimensional electron systems on either side of the L-junction (with no tunnel barrier) have different filling factors, according to the normal component of the magnetic field. For a range of tilt angle, the normal B can even switch sign. We perform transport across this abrupt junction between various IQHE and FQHE filling factors, and observe a new class of 4-terminal conductances that satisfy the Landauer-Büttiker formalism.

Quantum transport in carbon nanotubes and DNA molecules

S.Guéron, A.Kasumov, M.Kociak, ,B.Reulet, D.Klinov and H.Bouchiat
Laboratoire de Physique des Solides
Université Paris Sud (France)

We will present measurements of the conductivity of DNA molecules and carbon nanotubes at low temperature. We will present measurements of suspended ropes of single walled carbon nanotubes nanosoldered into good electrical contact with measuring pads. In such well connected systems, we do not observe Coulomb blockade at low temperature. On the contrary, we find that micrometer-long ropes of single walled carbon nanotubes can undergo a superconducting transition below 1 Kelvin. This is a rare example of a superconducting system containing less than a few hundreds of conducting channels. We have also measured the conductivity of a few DNA molecules connected to metal electrodes a few hundred nanometers appart. We find that at room temperature the DNA strands are conducting, with a typical resistance of 100 kOhms per strand. When the contacts are made of superconducting Re/C, we even measure a weak superconducting proximity effect below the critical temperature of the contacts. This indicates not only that DNA can conduct electricity, but also that it is a quantum coherent conductor over a few hundred nanometers.

Finite-size effects and spin-charge separation in tunneling between parallel quantum wires

Bertrand I. Halperin and Yaroslav Tserkovnyak
Harvard University, USA
Ophir Auslaender and Amir Yacoby
Weizmann Institute, Israel

Coulomb Drag at $\nu_T=1$: The Phase Transition from the Weakly Coupled State to the Interlayer Coherent State

Melinda Kellogg
California Institute of Technology, Pasadena, USA

Bilayer two dimensional electron systems with low electron density and small layer separation can enter an interlayer coherent state when the total filling factor of the y m n ($\nu_T=1$). Some dramatic manifestations of this state are the observations of the quantum Hall effect, Josephson-like interlayer tunneling and quantized Hall drag. The latter is observed when the system is set up in the transport configuration known as Coulomb drag. For this measurement a current is driven through just one of the layers while the voltage is monitored in the other. The ratio of this voltage to the current is called the drag resistance, and it is a highly sensitive probe of the interlayer electron interactions. I will present Coulomb drag data of our bilayer system (a GaAs/AlGaAs double quantum well heterostructure) as it transits from the weakly coupled phase to the interlayer coherent phase as the effective layer separation is reduced. We observe a remarkably large peak in the longitudinal drag midway through the phase transition, reaching a maximum value of n arly 9 kΩ q ar .

Strong enhancement of the valley splitting in a 2D
electron system in silicon

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A two-dimensional (2D) electron gas in (100)-silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) is a unique double-layer electron system in which the valley index is identical with the isospin quantum number. One can therefore apply to this system a good deal of recent theoretical work on double-layer electron systems. Strong interlayer correlations are obviously the case in this system and thus the lowest energy charge-carrying excitations are expected to be nontrivial isospin textures – skyrmions or merons – depending upon interlayer separation [1,2].

We perform, for the first time, low-temperature measurements of the chemical potential jump across the valley gap at the lowest filling factors $\nu=1$ and $\nu=3$ in a 2D electron system in high-mobility (100)-silicon MOSFETs using a magnetocapacitance technique. For both filling factors, the value of valley gap turns out to be strongly enhanced compared to the theoretically predicted single-particle value [3]. The valley gap enhancement decays rapidly with ν so that no enhancement is observed for $\nu=5$. To our surprise, the data are best described by a *linear* increase of the valley gap with B (or n_S). This fact is reliably established for $\nu=3$ where the systematic experimental error reflecting the level width contribution is small in the entire range of magnetic fields used. Extrapolation to B=0 of the linear magnetic field dependence of the $\nu=3$ gap yields a value which is consistent with the single-particle splitting. For filling factor $\nu=1$, the dependence of Δ, on B (or n_S) can also be described by a linear function, although the experimental uncertainty of the data for $\nu=1$ is markedly larger than that for $\nu=3$.

Our results for the enhanced valley splitting in silicon are similar to the puzzling proportional B dependence of the enhanced spin gap in the 2D electron system in AlGaAs/GaAs heterostructures [4,5]. According to the theoretical models of both nontrivial (iso)spin textures [1,2] and single spin-flip excitations [3], the gap enhancement is determined by the Coulomb interaction energy, $E_C=e^2/\varepsilon l$ (where $l=(\hbar c\ B)^{1/2}$ is the magnetic length). For strong enhancements, the many-body gap should thus have a $B^{1/2}$ dependence. This is in contradiction to the linear increase with magnetic field of the enhanced valley gap in Si MOSFETs and spin gap in GaAs [4,5]. [1] S.L. Sondhi et. al., *Phys. Rev. B* **47**, 16419 (1993). [2] K. Yang et. al., *Phys. Rev. Lett.* **72**, 732 (1994). [3] T. Ando, A.B. Fowler, and F. Stern, *Rev. Mod. Phys.* **54**, 437 (1982). [4] A. Usher et. al., *Phys. Rev. B* **41**, 1129 (1990). [5] V.T. Dolgopolov et. al., *Phys. Rev. Lett.* **79**, 729 (1997).

Measurement of Thermal Properties at Mesoscopic Scales

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The thermal properties of nanoscale materials are of fundamental interest and also play a critical role in controlling the performance and stability of nanodevices made of these materials. However, the measurements of thermal properties of nanomaterials at a mesoscopic scale have been technically challenging problems. We have fabricated submicron scale devices hybrided with nanoscale materials using state-of-art microfabrication thechniques. The thermal conductivity and thermoelectric power of carbon nanotubes and other nanowires have been measured at mesoscopic levels and exhibit distinticvely different behaviors from bulk material measurement.

Superconducting correlations for nanoparticles and their large orbital magnetic response

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We start by considering the reduced BCS Hamiltonian for a metallic grain with a finite number of electrons. Using an exact solution, we study the crossover between the regime of ultrasmall grains, in which the level spacing d is larger than the superconducting gap Δ, and the regime of small grains, where $\Delta > d$. We find a new scale in the latter range defined by the condition $\omega_D d > \Delta^2 > d^2$ where, as in the ultrasmall regime, the correlations of the levels further than Δ from the Fermi energy, neglected in the BCS approximation, are of prime importance. These correlations result in the condensation energy being much larger than that given by the BCS approximation. This thus gives a new, stronger, condition for the validity of the BCS approximation. For the ring geometry, the A-B flux dependence of the above correlation energy is strong, leading to a relatively large slope of the persistent current vs. flux at zero flux. The possible relevance of this to normal persistent currents is discussed. The model of, both repulsive and attractive, short-range interactions is considered as well. The difficulties of the conventional treatment are identified.

Possible New States of Interacting Composite Fermions

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Much of the present day phenomenology of the fractional quantum Hall effect can be understood by neglecting the interactions between composite fermions altogether. For example, the fractional quantum Hall effect at $\nu=n/(2pn\pm1)$ corresponds to the integral quantum Hall effect of composite fermions, and the compressible state at $\nu=1/2p$ to the Fermi sea of composite fermions. Away from these filling factors, the residual interaction between composite fermions will determine the nature of the ground state, which may be revealed as experiments improve. In this talk, I will present recent theoretical studies, done in collaboration with S.Y. Lee, S.S. Mandal, and V.W. Scarola, that deal with the residual interaction between composite fermions. These studies suggest the possibility of various kinds of states of composite fermions under appropriate conditions, for example: stripes, bubble crystal, paired state, or fractional quantum Hall effect. The limitations of the model and the relevance of the results to experiment will be discussed.

Spin-polarization in the lowest landau Level

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The possible spin-polarization of fractional quantum Hall states at filling factors 2p/(2pn+1) and (2p+1)/(2pn+1) are usually inferred from the energy-level structure of the corresponding composite Fermions (CF). This spectrum is controlled by the strength of the Zeeman (E_Z) and the Coulomb energy (E_C). At a given filling factor, the ratio $\eta = E_Z/E_C$ may be varied experimentally by tilting the two-dimensional electron gas with respect to the total magnetic field H, keeping the normal component to the sample constant. At half filling, the CF picture predicts two Fermi disks for each polarization which relative area (and spin-polarization) depends smoothly on η up to a critical value η_c when the system reaches full polarization. This behavior is well reproduced in experiments [1] with a linear dependence of $P(\eta)$ below η_c. At $\nu=1/3$, the spin polarization at low temperature is found to be complete for all values of η accessible in experiments. This is consistent with the QH ferromagnetic state expected at this filling factor. On the other hand, the thermal depolarization follows a one parameter scaling with scaled Zeeman energy $e_z=E_Z/k_BT$, *instead* of the two-parameter scaling expected for a 2D quantum Hall ferromagnet with e_z and $\rho_c=E_c/k_BT$, the scaled spin-stiffness. At $\nu=2/3$, a remarkable behavior of the polarization is observed as a function of η [2]. Below a critical value of η, the polarization jumps abruptly from P=1 to another quantized value of P close to 3/4. The same transition to a "3/4 polarized state" is observed at the same critical value of $\eta_c(2/3)$ on two different samples. This partially polarized state at $\nu=2/3$ is also incompressible. [1] N. Freytag, M. Horvatic, C. Berthier, M. Shayegan, L.P. Lévy, cond-mat/0205306. [2] N. Freytag, Y. Tokunaga, M. Horvati, C. Berthier, M. Shayegan, and L. P. Lévy, Phys. Rev. Lett. **87**, 136801 (2001) ; S. Melinte, N. Freytag, M. Horvatic, C. Berthier, L.P. Levy, V. Bayot and M. Shayegan, Phys Rev. Lett. **83**, 354 (2000).

Competition between antiferromagnetism and Kondo effect in the non-equilibrium transport properties of double quantum dots

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It is now well established that quantum dots (QD's) are artificial realizations of the Anderson model [1,2] and, then, behave as Kondo impurities at temperatures below the Kondo temperature T^0_K. In view the experimental advances in the study of quantum coherence in double quantum dots (DQD's) [3], it is thus a timely question to ask what happens when two QD's in the Kondo regime are coupled. As it was shown [4] this system can be regarded as an artificial version of the two-impurity Kondo problem. The theoretical study of the two-impurity problem was pioneered by Jones et al, [5]. They demonstrated that the competition between Kondo effect and antiferromagnetic (AF) ordering appears when J/T^0_K=2.2, where J is the exchange constant. So far, the theoretical efforts have been concentrated on studying linear transport through DQD [5] in the regime where this competition comes into a play and nonlinear transport has been lacking. Here, we report a theoretical study of nonlinear transport through a DQD in two different configurations, namely, when the two dots are coupled in a series and when they are in parallel. In DQD coupled in a series the AF interaction stems from virtual double occupation processes whereas for the parallel case is due to a strong electrostatic interdot interaction. From our results we prove that the nonlinear transport for both configurations is strongly affected in the region where AF interaction competes with the Kondo effect. We find that the differential conductance at T=0 directly measures the transition from a Kondo state to an AF spin-singlet state. The transition manifests as an observable splitting in the differential conductance In addition, we

find that for serial DQD's the transition is smooth whereas for the parallel case this transition is a first order jump occurring at (J/T_K)_c. Here, T_K is the Kondo temperature of the coupled system~[7] and (J/T_K)_c=2.5. Furthermore, for the parallel case we find that when (J/T_K)>(J/T_K)_c the differential conductance presents two maxima at finite voltage (V=J, -J) showing a splitting of 2J. Importantly, further increasing J/T_K does not change the value of this splitting allowing one to measure J experimentally.

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Mesoscopic frustrated phase separation in electronic systems

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Generically in density driven first order transitions one expects a range of densities (determined by Maxwell construction) where different phases coexist. In condensed matter one often encounters first order phase transitions driven by the electronic density (Wigner crystallization, Mott-Hubbard metal-insulator transitions, Manganites, etc. etc). However phase separation is severely hampered by the long range Coulomb interaction. We study a mixed state composed of self-organized inhomogeneities of one phase hosted by the other phase. A general analysis which generalizes Maxwell construction can be done in the case in which the inhomogeneities are on a mesoscopic scale. We briefly discuss applications to the 2-d electron gas, the manganites, the cuprates and neutron stars and show experimental evidence for self-organized mesoscopic phenomena.

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Superfluid Properties of Double-Layer Quantum Hall Ferromagnets

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Strong interactions can change a many-electron ground state qualitatively, for example by changing a metal into a Mott insulator or by giving rise to a ground state with superconducting or ferromagnetic order. For two-dimensional (2D) electrons in a perpendicular magnetic field, independent electrons occupy Landau levels with a macroscopic degeneracy proportional to the magnetic field strength. In the quantum Hall regime interactions are always strong compared to the Landau level width and samples where they are strong compared to disorder are now grown routinely. In such samples, analogs of various different behaviors familiar from strongly interacting bulk metals can occur, even in the same sample, depending on the Landau level filling factor ν and on details of the sample geometry. For example Laughlin's

incompressible state at $\nu=1/3$ is the quantum Hall analog of a Mott insulator. In this talk I will discuss double-layer quantum Hall systems at total filling factor $\nu=1$. For sufficiently small layer separations d, this system has a broken symmetry round state [1] that can be regarded either as an easy-plane ferromagnet or as an excitonic Bose condensate. This state exhibits superfluid [2] behavior for currents that flow in opposite directions in the two layers. I will discuss recent experiments [3] that probe the superfluid properties of these systems and discuss analogies between these systems and thin film ferromagnets. [1] For a review see S.M. Girvin and A.H. MacDonald edited by S. Das Sarma and Aron Pinczuk (Wiley, New York, 1997). [2] X. G. Wen and A. Zee, Phys. Rev. Lett. **69**, 1811 (1992); Phys. Rev. B **47**, 2265 (1993); Z. F. Ezawa and A. Iwazaki, Int. J. Mod. Phys. B **6**, 3205 (1992); Phys. Rev. B **48**, 15189 (1993); Kun Yang et al., Phys. Rev. Lett. **72**, 732 (1994); K. Moon et al., Phys. Rev. B **51**, 5138 (1995); Jordan Kyriakidis and Leo Radzihovsky, preprint [arXiv:cond mat/0011050] (2000). Ramin Abolfath and A.H. MacDonald, in preparation (2000). [3] I.B. Spielman, J.P. Eisenstein, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. **84**, 5808 (2000); I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **87**, 036803 (2001); M. Kellogg, I.B. Spielman, J.P. Eisenstein, L.N. Pfeiffer, K.W. West [cond-mat/0108403].

Coherence and Spin in 2,1, and 0D systems

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This talk will concern quantum transport signatures of spin in 2D 1D and 0D GaAs systems. In 2D, we present gate-controlled crossover from weak localization to antilocalization. In 1D, we discuss 0.7 structure, and its relation to possible Kondo physics, and also show that a quantum point contact can be used as a spin injector and spin detector. in 0D, we present antilocalization in quantum dots with strong spin orbit scattering and also show how a dot can be used as a spin-polarized injector of spin with a gate-controlled spin orientation.

Generation of Entangled Multi-Spin States in a Semiconductor Quantum Well

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We propose and demonstrate experimentally a novel method to generate entangled many-particle wavefunctions involving Zeeman-split spin states of *non-interacting* paramagnetic impurities in a crystal host. Specifically, we use ultrafast optical pulses and coherent techniques to produce entangled states of electrons belonging to at least three donors and, separately, at least two Mn^{2+} ions in a $Cd_{1-x}Mn_xTe$ quantum well. Our approach, relying on the exchange interaction between localized excitons and the impurities, can in principle be applied to entangle a large number of spins.

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Electron states and transport properties of biomolecules

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Ferromagnetism in III-V Semiconductors and Their Heterostructures

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Carrier-induced ferromagnetism in magnetic III-V's has introduced magnetic cooperative phenomena to III-V heterostructures and a number of new structures and phenomena have been explored and demonstrated. In these structures, magnetism plays an

important role in determining semiconductor properties and semiconducting properties control magnetism. These developments unlock ways to manipulate the spin degree of freedom in semiconductors often neglected in modern semiconductor electronics. The present study and related efforts in other laboratories may lead us to a new form of electronics, semiconductor spintronics, where both charge and spin of electrons play a critical role [1]. [1] H. Ohno, F. Matsukura, and Y. Ohno, *JSAP International*, No. 5, Jan. 2002, pp. 4-13. (available at http://www.jsapi.jsap.or.jp/)

More fractions from the quantum Hall zone: Some with a special twist

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H.L. Stormer *(Columbia University and Bell Labs)*
D.C. Tsui *(Princeton University)*
L.N. Pfeiffer, K.W. Baldwin, and K.W. West *(Bell Labs)*

In this talk, we are going to present new experimental results carried out in an exceptionally high quality GaAs/AlGaAs quantum well sample of density $n \sim 1 \times 10^{11}$ cm^{-2}. For the first time, we observed the formation of the FQHE state at nu=4/11, manifested by a very deep Rxx minimum and a developing Hall plateau. The T-dependence measurement shows that its energy scale is very small, ~ 30mK. In tilted magnetic field experiments the $\nu=4/11$ state is very stable in the presence of an in-plane magnetic field. Our data clearly indicate the existence of a spin polarized state at $\nu=4/11$. This observation deviated from the result of few-particle calculations, which find such a state not to be stable. Since the $\nu=4/11$ state represents the first scrutinized state not belonging to any primary FQHE sequences, our observations clearly demonstrates that composite fermions are interacting.

From Cooper pairs to Luttinger liquids with one-dimensional bosonic atoms

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We propose a situation for a one dimensional gas of bosonic atoms in an optical lattice in which highly correlated fermionic phenomena, such as Cooper pair formation or Luttinger liquid behaviour, may be observed. The key idea is to consider bosonic atoms with two internal states in such a situation that atoms with the same spin interact repulsively and stronger than atoms with different spin. The system then exhibits similar behaviour to a system of {\em interacting fermions}. By tuning the sign and strength of the interaction between atoms with different spin, it is possible to move from a "superconducting" regime, in which the system exhibits atomic pairing, to a Luttinger liquid regime.

Metastable phase in the quantum Hall ferromagnet

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QH ferromagnets with easy-axis – Ising – anisotropy have been the subject of an intense research effort in the last few years. The two hallmarks of Ising QH ferromagnets are observation of hysteresis and collapse of the QH state close to Landau level crossing. Both these two manifestations are particularly evident in magneto-transport experiments and have been studied in different material systems in integer and fractional QH regimes. These features can be understood by invoking the presence of disorder-induced randomly distributed magnetic domains and their evolution in the complex energy landscape close to level crossing. This talk presents our recent capacitance measurements that reveal an unstable phase of electrons in gallium arsenide quantum well that occurs when two Landau levels with opposite spin are brought close to degeneracy by applying a gate voltage. This phase emerges at low temperature and displays a peculiar non-

equilibrium dynamical evolution. The relaxation dynamics is found to follow a stretched exponential behavior and correlates with hysteresis loops observed by sweeping the magnetic field. We show that different metastable magnetic domain configurations are involved in the relaxation process in a way that is equivalently tunable by a change in gate voltage or temperature.

*Work done in collaboration with V.Piazza, F. Beltram and W. Wegscheider

Ultrafast Nonlinear Optical Response of Strongly Correlated anostructures: Dynamics in the qantum Hall Effect Regime

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We present a systematic theory for studying the coherent ultrafast nonlinear optical response of strongly correlated systems and discuss an example where the Coulomb correlations dominate. We separate out the Hartree--Fock from the correlation contributions to the third--order nonlinear polarization, and describe the non--Markovian memory, dephasing, correlation, and shake--up effects that arise from the non--instantaneous interactions between the photoexcited carriers and collective excitations. We identify the signatures, in the time and frequency dependence of the four--wave--mixing (FWM) spectrum, of the inter--Landau level magnetoplasmon excitations of a two--dimensional electron gas (2DEG) in a strong magnetic field. We predict a resonant enhancement of the lowest Landau level (LL) FWM signal, a strong non--Markovian magnetoexciton dephasing, a symmetric FWM temporal profile, and strong oscillations as function of time delay, of quantum kinetic origin. We show that the correlation effects can be controlled experimentally by tuning the central frequency of the optical excitation between the two lowest LLs.

New MBE technique for monolayer smooth quantum wells and wires allowing observation of lasing in a single quantum wire

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We describe a new MBE high temperature anneal that promotes remarkable smoothing of the [110] GaAs surface after cleaved-edge overgrowth (CEO). Until this technique all quantum wells grown by MBE have had barrier walls pocked by monolayer pits, bumps, and step edges. Because CEO is able to start from a perfectly smooth step-free cleaved AlGaAs surface, and because we are able to supply just sufficient GaAs beam flux to grow for example exactly 30 GaAs monolayers (ML), we are now able using this anneal to grow AlGaAs/GaAs/AlGaAs [110] quantum wells that are free of all ML-stepedges, pits, or islands for tens of microns in spatial extent. The PL from these atomically smooth quantum wells is x8 sharper than from the wells without the anneal. This PL sharpness of [110] quantum wells translates to x8 sharpness improvement in the PL of our cleaved-edge overgrowth T-quantum wires, and this reduction in inhomogeneous broadening translates to a lasing threshold reduction for our quantum wire lasers by a corresponding amount. This new ability the achieve a lower laser threshold together with a redesign involving tighter photon coupling to our quantum wire have allowed us to achieve lasing from an isolated single quantum wire. All of our previous work has involved 15 to 22 quantum wires excited together in a single optical cavity.

Spectroscopy of composit fermions: Landau levels and residual interactions

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Low-dimensional electron systems in quantum structures offer unique venues for the exploration of fundamental interactions. In two-dimensional systems composite fermion quasiparticles interpret experimental results in the quantum Hall regimes. Inelastic light scattering methods access directly the quasiparticle excitations of these quantum liquids. Light scattering studies yield spectra of excitations modes that are striking manifestations of the electron interactions. This talk presents results of recent light scattering experiments in two- dimensional systems. The experiments access the lowest excitations of spin and charge of composite fermions. They reveal energies vs momentum dispersions of composite fermion excitations. We find direct evidence of well-defined structure of energy levels (Landau-levels) of composite fermions in states of the fractional quantum Hall liquid such as those at Landau level filling factor $\nu=1/3$ and $\nu=2/5$. More complex behaviors of quasiparticle excitations are observed at the intermediate filling factors. The experiments considered here cover the full range $2/5 > \nu > 1/3$. At these filling factors, intermediate between two major fractional quantum Hall states, low-lying spin excitations of composite fermions are below the Zeeman energy. These excitation modes have unexpected behavior that could be attributed to significant residual interactions among composite fermions.

(*) In collaboration with Irene Dujovne, Cyrus Hirjibehedin, Moonsoo Kang, Brian Dennis, Loren Pfeiffer and Ken West.

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Self-consistent theory of pair distribution functions and effective interactions in quantum Coulomb liquids

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We use a density-functional theoretical approach to set up a computationally simple self-consistent scheme to calculate the pair distribution functions and the effective interactions in quantum Coulomb liquids. We demonstrate the accuracy of the approach for different statistics and space dimensionalities by reporting results for a three-dimensional boson plasma and for a two-dimensional electron gas over physically relevant ranges of coupling strength, in comparison with Quantum Monte Carlo data.

Exact-Exchange Density Functional Theory applied to strongly inhomogeneous electron gases

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The first developments and applications of Exact-Exchange Density Functional Theory (XX-DFT) for two-dimensional electron gases[1] (2DEG) and strongly inhomogeneous metallic systems will be shown [2] . The formalism avoids the usual Local Density Approximation (LDA) of the exchange energy per particle, in terms of the *local* exchange energy per particle of the *homogeneous* electron gas. Instead, the XX formalism start from the exact exchange energy of the 2DEG, which is an explicit functional of the subband envelope wave functions and their occupancies. The XX-DFT *local* exchange potential is then obtained by taking functional derivatives with respect to the "shape" of the wave functions, and the occupancies. The applications to be discussed include: i) direct explanation of experimental results by Goñi *et al.*, who found an abrupt occupancy of the first-excited subband when the chemical potential touches the bottom of

this subband, and ii) comparison with state of the art numerical simulation of a strongly inhomogeneous metallic systems [3]. Both cases are beyond the reach of LDA. [1] A. R. Goñi, U. Haboeck, C. Thomsen, K. Eberl, F. A. Reboredo, C. R. Proetto, and F. Guinea, Phys. Rev. B **65**, 121313 (R) (2002). [2]S. Rigamonti, F. A. Reboredo, and C. R. Proetto (unpublished). [3]M. Nekovee, W. M. C. Foulkes, and R. J. Needs, Phys. Rev. Lett. **87**, 036401 (2001).

Raman signatures of quantum phases in artificial molecules

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Coupled quantum dots - also called artificial molecules - extend the possibility of exploring the fundamentals of electronic correlation, since the tunneling energy is added to the energy scales set by the confining potential, the Coulomb interaction, and the magnetic field B. In this work we focus on the high B regime, where the field quenches the kinetic energy driving electrons into the ``classical'' limit; hence, carriers tend to localize in a Wigner molecule. Sweeping the inter dot distance d one can change the tunneling energy. At small d tunneling dominates and the system behaves as a unique coherent system. At large d tunneling is suppressed, the only relevant parameter for the now well separated dots being the ratio between intra- and inter-dot interaction. In between, the tunneling energy competes with other energy scales and, as we will show, gives rise to a complex phase diagram. In order to investigate the transition between the different regimes, we perform exact diagonalizations of the electron Hamiltonian up to N=6 electrons within a Configuration Interaction approach. By analyzing the two-particle correlation function, we find that, for N=6, at small d electrons arrange at the vertices and the center of a regular pentagon (Phase I). At a critical value an abrupt transition takes place to Phase II, with electrons sitting at the vertices of a regular hexagon. At sufficiently large d the structure evolves into two isolated dots, coupled only through Coulomb interaction, where electrons in each dot sit at the vertices of an equilateral triangle, the two triangles being rotated by 60 degrees (III). It is remarkable that the configuration corresponding to II is classically unstable, and it is therefore stabilized by the tunneling- induced quantum fluctuations. Moreover, in contrast to I and III, II is liquid-like, as shown by the angular profiles of the correlation function. We interpret this solid-liquid-solid sequence as a 2D-3D-2D transition [1]. The calculated Raman spectra show specific features for each phase. First, to excite carriers across the symmetric-antisymmetric gap of the double dot structure, incoming photons must have a component along the dot axis; therefore, only I is visible for in plane scattering. II and III, which have a maximum intensity for incoming light at 45 degrees, can still be distinguished from the energy position and the different scaling with d, since the tunneling energy, null in III, is involved in the optical excitations for II.

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Competing orders in the cuprate superconductors

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I will describe and interpret an innovative series of recent experiments on a variety of cuprate superconductors. These observations support the proposal that ground state correlations in the cuprates can be described by a common theory of competine order parameters in the doped Mott insulator, and of proximity to quantum phase transitions associated with them. The competing orders can be tuned by an applied magnetic field, and I will present theoretical predictions for the phase diagram as a function of doping concentration and magnetic field strength, and for the structure of the field-induced vortices in the superconductor. A theory for a spin density wave ordering transition in this phase diagram simultaneously describes a variety of

observations with a single set of typical parameters: the field dependence of the elastic neutron scattering intensity, the absence of satellite Bragg peaks associated with the vortex lattice in existing neutron scattering experiments, and the spatial extent of the charge order in STM experiments. The microstructure of the charge order observed in STM will also be related to theoretical predictions arising from studies of magnetic transitions
in Mott insulators and superconductors.

Magnetism, Transport and Tunneling in Ferromagnetic Semiconductor Heterostructures

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The molecular beam epitaxy (MBE) of ferromagnetic semiconductor heterostructures provides model systems for exploring fundamental issues in semiconductor spintronics. We provide an overview of hybrid heterostructures that combine the ferromagnetic semiconductor (Ga,Mn)As with conventional III-V and II-VI semiconductors, as well as with the metallic ferromagnet MnAs. We first discuss the basic properties of (Ga,Mn)As, highlighting the delicate interplay between disorder and magnetism in this complex material. In particular, a consistent annealing protocol modifies the disorder in as-grown samples, yielding a conventional magnetization that can be compared with predictions from mean field theory. Finally, we demonstrate two new classes of spintronic heterostructures: (a) hybrid ferromagnetic metal/semiconductor tunnel junctions that probe spin injection into semiconductors using all-electrical techniques and (b) hybrid ferromagnetic/semiconductor photodiodes that serve as toy spintronic "devices" whose photo-response is magnetically controlled. This work is carried out in collaboration with S. H. Chun, K. C. Ku, S. J. Potashnik, and P. Schiffer, and is supported by grants from DARPA, ONR and NSF.

Canted Antiferromagnetic Phase in Vertical Quantum Dot Systems

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We study different magnetic phases in vertical double quantum dots in the presence of in-plane magnetic fields. We consider parabolic quantum dots with a large number of electrons (N=31 and N=32), which justifies the use of a Hartree-Fock approximation. We analyze the energy and the total spin components of the system's ground state as a function of the interdot tunneling and calculate the total isospin and the interdot coherence at a fixed interdot distance. The main findings of our work are: i) We observe a canted antiferromagnetic phase in a double quantum dot with an even number of electrons, in the presence of an in-plane magnetic field (not along the growth direction). This state is proven to stem from the subtle competition between intradot and interdot exchange interaction in addition to the external perturbations (namely, tunneling and Zeeman energies). ii) For an odd number of electrons, a canted phase is predicted as well at arbitrarily small Zeeman splittings. We propose a simple model which explains qualitatively our results and which allows to deal with more complex quantum dots systems. We have found that the canted phase is favored at the expense of the ferromagnetic (fully spin-polarized) phase for long quantum-dot superlattices

Theory of quantum annealing of Ising spin glasses

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Quantum annealing is a relatively new and fascinating idea on how to use quantum fluctuations, instead of thermal fluctuations, to anneal a complex system towards its (classical) minimal energy state. Experimentally, quantum annealing was recently realized in a disordered spin 1/2 Ising magnet, were it was found to be more

effective than its classical, thermal counterpart. Stimulated by this experimental finding, we have addressed the problem theoretically. Comparing classical and quantum Monte Carlo annealing protocols on the random two-dimensional Ising model we have confirmed the superiority of quantum relative to classical annealing. We have also proposed a theory of quantum annealing, based on a cascade of Landau-Zener tunneling events, which rationalizes these findings. For both classical and quantum annealing, the residual energy after annealing decreases only as $1/[\log(\tau)]^z$, where τ is the total annealing time and z is a positive exponent, but the quantum case has a larger value for z which makes it faster. A discussion of other possible applications will be given.

Mn_{12}-acetate: a prototypical "single-molecule magnet"

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Mn_{12}-acetate and Fe_8 are prototypical magnetic molecular crystals, materials that are interesting for behavior that is borderline between the classical and quantum mechanical regimes, and for their potential applications for high-density data storage and quantum computation. The "single-molecule magnet" Mn_{12}-acetate consists of a large (Avogadro's) number of nominally identical magnetic molecules, each of sizable total spin S=10, regularly arranged on a tetragonal lattice with large uniaxial anisotropy on the order of 60 K. Below the blocking temperature of ~ 3 K, steps in the (hysteretic) magnetization curve at well-defined magnetic fields signal enhanced relaxation due to tunneling of the spin magnetic moment via energy levels that cross on opposite sides of the potential barrier [1]. Background information will be given on the structure of the molecule, the Hamiltonian that models its behavior, and the tunneling process that gives rise to the "steps". Data will be shown that indicate there is an abrupt transition between thermally activated and pure quantum tunneling [2]. The symmetry-breaking process that drives the observed tunneling that yields magnetic relaxation will also be discussed [3]. Supported by NSF grant DMR-0116808. [1] J. R. Friedman, M. P. Sarachik, J. Tejada, and R. Ziolo, Phys. Rev. Lett. **76**, 3830 (1996). [2] A. D. Kent, Y. Zhong, L. Bokacheva, D. Ruiz, D. Hendrickson, and M.P. Sarachik, Europhys. Lett. **49**, 521 (2000); K. M. Mertes, Y. Zhong, M. P. Sarachik, Y. Paltiel, H. Shtrikman, E. Zeldov, E. Rumberger, D. N. Henderson, and G. Christou, Europhys. Lett. **55**, 874 (2001). [3] K. M. Mertes, Y. Suzuki, M. P. Sarachik, Y. Paltiel, H. Shtrikman, E. Zeldov, Evan Rumberger, D. N. Henderson, and G. Christou, Phys. Rev. Lett. **87**, 227205 (2001).

Magneto transport in GaAs/AlAs 2D Carrier Systems

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We will present the results of our transport measurements, at high magnetic fields, in AlAs two-dimensional (2D) carrier systems. The 2D electrons in AlAs differ from the usual GaAs 2D electrons in that they possess an anisotropic Fermi surface, have a much larger effective mass and Lande g-factor, and can also occupy multiple conduction band valleys in the Brillouin zone. The presentation highlights will include measurements of the integer and fractional quantum Hall effect in AlAs 2D electrons, with an emphasis on the magnetic transitions between the quantum Hall ferromagnetic states in tilted magnetic fields. We will also present some recent measurements of the spin-polarization of various dilute 2D carrier systems (electrons in GaAs and AlAs, holes in GaAs) in the presence of an in-plane magnetic field. The data are surprising as they show a decreasing effective g-factor with decreasing density; this is contrary to the common expectation that the effective g-factor should increase and eventually diverge as the 2D system is made more dilute.

treatment of disorder of these materials. Our results within this 'minimal disorder' theory involving transport and optical properties are in good agreement with current experimental trends, both in magnitude and transport anisotropy, and indicate different limits of possibilities in these materials important within a physical and technological context.

Oscillating sign of drag in high Landau levels

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Motivated by experiments, we study the sign of the Coulomb drag voltage in a double layer system in a strong magnetic field. We show that the commonly used Fermi Golden Rule approach implicitly assumes a linear dependence of intra-layer conductivity on density, and is thus inadequate in strong magnetic fields. Going beyond this approach, we show that the drag voltage commonly changes sign with density difference between the layers. We predict that in the Quantum Hall regime the Hall and longitudinal drag resistivities are comparable. Our results are also relevant for pumping and acoustoelectric experiments.

Magnetic and transport properties of metallic (III,Mn)V magnetic semiconductors

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The interplay between the localized Mn moments and the hole carriers in (III,Mn)V semiconducting materials give rise to novel ferromagnetic ordered states whose magnetic, transport and optical properties are richer than those of conventional itinerant electron ferromagnets. The unique properties of these states are intimately tied to the strong valence-band spin-orbit coupling, and the sensitivity of their magnetic state to growth conditions, doping, and external fields. We present theoretical results for several magnetic parameters, transport coefficients, and ac-conductivity that apply to metallic (III,Mn)V ferromagnetic semiconductors. Many of the predicted properties of these materials within this phenomenological model (such as critical temperature, transport anisotropy, anomalous Hall effect, etc.) are in good quantitative agreement with experimental results in spite of the simplified

2DEGs in HIGFETs: The Power of the Knob

Horst L. Stormer
Columbia University and Bell Labs, USA

Heterojunction Insulated Gate Field Effect Transistors (HIGFETs) have provided us with tunable density two-Dimensional Electron Gases (2DEGs). Today's HIGFETs can reach peak mobilities beyond 10^7 $cm^2/Vsec$ and are ideally suited to address some outstanding issues in 2D correlated electron physics in which electron density tunability improves our ability to make new discoveries or to make better connections between experimental results and theoretical analysis. Using three examples I will try to support this view.

Ultrafast photoluminescence of an exciton condensate

Carlos Tejedor
Universidad Autonoma de Madrid, Spain

The condensation of electron-hole pairs in semiconductors was theoretically proposed many years ago but such a macroscopic quantum coherent state has proved elusive from the experimental point of view. In this talk we propose a framework to experimentally detect that condensation. We have studied theoretically the transfer of coherence from a quantum well electron-hole condensate to the light it emits. As a function of density, the electron-hole system evolves from being fully coherent for the low-density Bose-Einstein condensate to a chaotic behavior for a high-density BCS-like state. This degree of coherence is transferred to the light emitted in a damped oscillatory way in the ultra-fast regime. Additionally, the photon field exhibits squeezing properties during the

transfer time. Work in collaboration with A. Olaya-Castro, F. Rodriguez and L. Quiroga

Nano-Scale Studies of Low-Dimensional Electron Systems by Low-Temperature Scanning Tunneling Spectroscopy (STS)

Roland Wiesendanger
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We have systematically studied 0D-, 1D-, and 2D- electron systems at InAs(110) surfaces by means of low-temperature scanning tunneling spectroscopy under ultrahigh vacuum conditions. The 0D system is realized by a tip-induced quantum dot which is formed as a result of local band bending underneath the STM probe tip. 1D electron systems were found near charged step edges of the InAs(110) surface while 2D electron systems were prepared by adsorption of submonolayers of Fe, Co, and Nb onto clean InAs(110). In all cases, the effect of atomic-scale defects on the electronic states were directly visualized in real space. Fluctuations in the local density of states could directly be related with electron scattering at impurities in the quantum wires and the 2D electron systems. Finally, the influence of external magnetic fields on the low-dimensional electron systems was studied in the presence of potential disorder. In high magnetic fields, the so-called drift states of the 2D electron system were mapped with a spatial resolution beyond the magnetic length scale. A direct comparison with the corresponding 3D electron system in the same InAs crystal will be made. [1] Chr. Wittneven et al., Phys. Rev. Lett. 81, 5616 (1998) [2] M. Morgenstern et al., Phys. Rev. Lett. 84, 5588 (2000) [3] D. Haude et al., Phys. Rev. Lett. 86, 1582 (2001) [4] M. Morgenstern et al., Phys. Rev. B 64, 205104 (2001) [5] R. Dombrowski et al., Phys. Rev. B 59, 8043 (1999) [6] M. Morgenstern et al. Phys. Rev. B 63, 201301 (2001)

Tunneling Spectroscopy of the Elementary Excitations in One Dimension

Amir Yacoby
Department of Condensed Matter, Weizmann Instutute of Science, Israel

We have measured the collective excitation spectrum of interacting electrons in one-dimension. The experiment consists of controlling the energy and momentum of electrons tunneling between two closely situated, parallel quantum wires in a GaAs/AlGaAs heterostructure while measuring the resulting conductance. The measured excitation spectrum clearly deviates from the non-interacting spectrum, attesting to the importance of Coulomb interactions. Notable is an observed %30 enhancement of the velocity of the main excitation branch relative to non-interacting electrons with the same density, a parameter determined experimentally. In short wires, 6 microns and 2 microns long, finite size effects, resulting from breaking of translational invariance, are observed. Finally, two independent manifestations of spin-charge separation are observed in the spectrum.

DNA-based nanostructures and molecular motors

Bernard Yurke
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The base sequence specificity of DNA makes it a versatile recognition molecule for use in the assembly of complex nanostructures. The free energy of hybridization, released as two DNA strands come together to form duplex DNA, can be utilized to induce nanostructures to perform mechanical work. Strand displacement allows one to operate such structures as cyclic engines.

POSTER CONTRIBUTIONS

Frictional magnetodrag between spatially separated two-dimensional electron gases mediated by virtual phonon exchange
S. M. Badalyan
Department of Radiophysics, Yerevan State University, 375025 Yerevan, Armenia

Phase-Breaking Effects in Superconducting Heterostructures: Theory and Experiment
Mikhail Belogolovskii
Donetsk Physical & Technical Institute, Donetsk, Ukraine

Synthesis and characterization of maghemite nanoparticles entrapped in pseudo single crystals of cyclodextrin
Daniele Bonacchi
University of Firenze, Italy

Spin-OLED: a possible application of spintronic in organic based devices
Ilaria Bergenti
Universita' di Parma, Facolta' di Fisica, Parma (Italy) and Istituto per lo Studio dei Materiali Nanostrutturati (ISMN) Bologna (Italy)

Josephson junction array as a quantum switch with a superconducting control line
Silvia Corlevi
Royal institute of Technology (KTH), Section of Nanostructure Physics and Stockholm Center for Physics, Astronomy and Biotechnology (SCFAB) (Sweden)

Electromodulation of charge transfer and the breathing mode of C60 on graphite
Miriam del Valle
Universidad Autónoma" of Madrid, (Spain)

Exchange-driven instability and spin polarization of the two-dimensional electron gas at zero magnetic field
Paula Giudici
Institut of Solid State Physics, TU Berlin, (Germany)

Nanomechanics with Carbon Nanotubes
Pablo Jarillo-Herrero
Quantum Transport Group, Department of Applied Physics, Delft University of Technology (The Netherlands)

Temperature dependent transport through molecules and quantum dots
Urban Lundin
Department of Physics, University of Queensland Brisbane (Australia)

Phase Separation and Phase Diagrams of Pr-Ca-Sr manganese oxides
Dario Niebieskikwiat
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Field-induced magnetic quantum phase transitions:
thermodynamic and dynamic properties of $TlCuCl_3$
B. Normand
Universitè de Fribourg, (Switzerland)

Bunching of Coulomb blockade peaks in Quantum dots at high magnetic fields
José Ignacio Perea
Universidad Autonoma de Madrid (Spain)

Localization in Artificial Disorder
Dimitri Pochine
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Nonequilibrium dynamics and Bose-Einstein Condensation of polaritons
D. Porras, C. Ciuti, J.J. Baumberg, and C. Tejedor.
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Inter-edge tunneling of quantum Hall states in the weak- coupling regime
Stefano Roddaro
NEST-INFM and Scuola Normale Superiore, Pisa (Italy)

Tunnel spectroscopy of a superconducting quantum bit

David Schaeffer Enno Bibow, Phillipe Lafarge, Laurent Lévy
CNRS LCMI, Grenoble High Magnetic Field Laboratory, Grenoble cedex 9 (France)

Joachim Sjostrand
Stockholm University

Spatial Dependence of Ferromagnetically-Imprinted Nuclear Spins in GaAs

Jason Stephens
University of California, S. Barbara (USA)

Josephson Energy dependent Switching Currents of a Cooper Pair Transistor

Jochen Walter
Royal Institute of Technology (KTH) Stockholm Center for Physics, Astronomy and Biotechnology (SCFAB) Section of Nanostructure Physics Stockholm, (Sweden)